

# MAXIM

## Low Voltage Step-Up DC-DC Converters

MAX654-659

### General Description

The MAX654-659 step-up DC-DC converters operate from low input voltages such as those supplied by single-cell batteries. They feature a low battery indicator and can run in standby mode to prolong battery life. A Power Ready output provides a means to control external circuitry when standby mode is used.

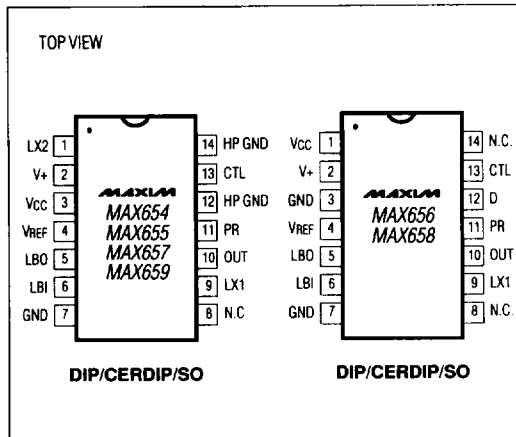
The performance characteristics of each device are listed in the following table. The MAX654/656/657 are optimized for single-cell input, while the MAX655/658/659 work best with two series alkaline or NiCad cells, or one lithium cell. The MAX654/655/657/659 contain an internal power MOSFET, while an external MOSFET is required with the MAX656/658.

PART	TYP INPUT RANGE (V)	OUT (V)	POWER SWITCH	OUTPUT (mA)
MAX654	1.15-1.56	5	Internal	40
MAX655	2.30-3.10	5	Internal	60
MAX656	1.15-1.56	5	Ext MOSFET	170
MAX657	1.15-1.56	3	Internal	60
MAX658	2.30-3.10	5	Ext MOSFET	110
MAX659	2.30-3.10	3	Internal	60

### Applications

- Battery-Powered Devices
- Single-Cell Instruments
- Pagers and Radio Controlled Receivers
- 4-20mA Loop Powered Instruments

### Pin Configurations



### Features

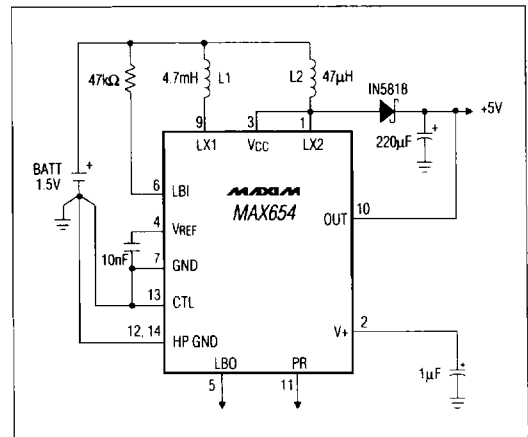
- ◆ +5V at 170mA from a Single-Cell Battery
- ◆ Guaranteed Start-Up at 1.15V
- ◆ Minimum Component Count
- ◆ Shutdown Mode—80µA Quiescent Current
- ◆ Low Battery Indication
- ◆ Power Ready Function

### Ordering Information

PART	TEMP. RANGE	PIN-PACKAGE
MAX654CPD	0°C to +70°C	14 Plastic DIP
MAX654CSD	0°C to +70°C	14 Narrow SO
MAX654C/D	0°C to +70°C	Dice
MAX654EPD	-40°C to +85°C	14 Plastic DIP
MAX654ESD	-40°C to +85°C	14 Narrow SO
MAX654MJD	-55°C to +125°C	14 CERDIP
MAX655CPD	0°C to +70°C	14 Plastic DIP
MAX655CSD	0°C to +70°C	14 Narrow SO
MAX655C/D	0°C to +70°C	Dice
MAX655EPD	-40°C to +85°C	14 Plastic DIP
MAX655ESD	-40°C to +85°C	14 Narrow SO
MAX655MJD	-55°C to +125°C	14 CERDIP

Ordering information continued on page 5-56.

### Typical Operating Circuit



# Low Voltage Step-Up DC-DC Converters

## ABSOLUTE MAXIMUM RATINGS

Peak Voltage at LX1 Pin	+16V	Operating Temperature	
Peak Voltage at LX2 or V <sub>CC</sub> Pin	+6.6V	MAX65XCXX	0°C to +70°C
Supply Voltage to L1	+15V	MAX65EXXX	-40°C to +85°C
Supply Voltage to L2, V <sub>CC</sub>	+5.6V	MAX65MXX	-55°C to +125°C
Peak Current, LX1	50mA	Power Dissipation	
Peak Current, LX2	1.6A	Plastic DIP (derate 10mW/°C above 70°C)	800mW
LBO Output Current	50mA	SO (derate 8.7mW/°C above 70°C)	695mW
Input Voltage, CTL, LBI (Note 1)	-0.3V to (V <sub>+</sub> + 0.3V)	CERDIP (derate 9.5mW/°C above 70°C)	750mW
		Storage Temperature	-65°C to +160°C
		Lead Temperature (Soldering, 10 Sec)	+300°C

Note 1: V<sub>+</sub> is generated at LX1. In low current mode, it is 4.5V to 5.6V (2.6V to 3.6V on MAX657, 659); in high current mode, it is 10V to 15V.

Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions above those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

## ELECTRICAL CHARACTERISTICS: MAX654, MAX656, MAX657

(GND = 0V, V<sub>BATT</sub> = 1.2V, T<sub>A</sub> = 25°C, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Output Voltage	V <sub>OUT</sub>	MAX654, MAX656	T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>	4.5	5.0	5.5	V
		MAX657	T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>	2.7	3.0	3.3	
Output Current	I <sub>L</sub>				See Table 1		mA
Minimum Input Voltage to LX1	V <sub>LX1</sub>	I <sub>L</sub> = 0μA			0.9	1.0	V
Minimum Startup Voltage to LX1	V <sub>LX1</sub>	I <sub>L</sub> = 0μA			1.1	1.15	V
Input Voltage to LX2	V <sub>LX2</sub>					5.6	V
Peak LX2 Switch Current	I <sub>LX2</sub>	MAX654, MAX657				1.5	A
Standby Current	I <sub>Q</sub>	I <sub>L</sub> = 0μA, CTL = Open				80	μA
Switching Frequency	f <sub>0</sub>	V <sub>BATT</sub> = 1.0V to 1.6V		15.5	18	24	kHz
		T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>				18	
LX2, D Switch Duty Cycle	%ON	MAX654, MAX656		66	75	80	%
		MAX657		50	66	75	
LX2, D Switch On Time	t <sub>ON</sub>	MAX654, MAX656		30	42	46	μs
		MAX657		23	37	44	
LX2 On Resistance	R <sub>DSON</sub>	MAX654, MAX657		0.40			Ω
D Output Saturation Current		MAX656	Source Sink			-25 100	mA
Low Battery Input Threshold Voltage	V <sub>LBI</sub>			1.12			V
Low Battery Input Threshold Tempco						-0.5	mV/°C
Low Battery Input Bias Current	I <sub>LBI</sub>					0.01	nA
Low Battery Output	V <sub>LBO</sub>	V <sub>LBI</sub> < 1.12V, I <sub>LBO</sub> = 1.6mA V <sub>LBI</sub> > 1.18V, I <sub>LBO</sub> = -1μA		V <sub>+</sub> -1		0.4	V
CTL Input Threshold	V <sub>CTL</sub>					0.7	V
PR Output	V <sub>PR</sub>	PR High, I <sub>PR</sub> = -1μA PR Low, I <sub>PR</sub> = 1mA		V <sub>OUT</sub> - 0.2 0.3		V	

# Low Voltage Step-Up DC-DC Converters

## ELECTRICAL CHARACTERISTICS: MAX655, MAX658, MAX659

(GND = 0V, V<sub>BATT</sub> = 2.4V, T<sub>A</sub> = 25°C, unless otherwise noted.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS	
Output Voltage	V <sub>OUT</sub>	MAX655, MAX658	T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>	4.5	5.0	5.5	V
		MAX659	T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>	2.7	3.0	3.3	
Output Current	I <sub>L</sub>	See Table 1					mA
Minimum Input Voltage to LX1	V <sub>LX1</sub>	I <sub>L</sub> = 0μA		0.9	1.0	V	
Minimum Startup Voltage to LX1	V <sub>LX1</sub>	I <sub>L</sub> = 0μA		1.0	1.5	V	
Input Voltage to LX2	V <sub>LX2</sub>				5.6	V	
Peak LX2 Switch Current	I <sub>LX2</sub>				1.5	A	
Standby Current	I <sub>Q</sub>	I <sub>L</sub> = 0μA, CTL = Open		40		μA	
Switching Frequency	f <sub>0</sub>	V <sub>BATT</sub> = 2.0V to 3.2V		15.5	18	24	kHz
		T <sub>A</sub> = T <sub>MIN</sub> to T <sub>MAX</sub>			18		
LX2, D Switch Duty Cycle	%ON	MAX655, MAX658		40	50	60	%
		MAX659		25	33	37	
LX2, D Switch On Time	t <sub>ON</sub>	MAX655, MAX658		18	28	35	μs
		MAX659		12	18	22	
LX2 On Resistance	R <sub>DSON</sub>		0.40		0.67	Ω	
D Output Saturation Current		MAX658	Source Sink		-25 100	mA	
Low Battery Input Threshold Voltage	V <sub>LBI</sub>		1.12		1.18	V	
Low Battery Input Threshold Tempco				-0.5		mV/°C	
Low Battery Input Bias Current	I <sub>LBI</sub>			0.01	10	nA	
Low Battery Output	V <sub>LBO</sub>	V <sub>LBI</sub> < 1.12V, I <sub>LBO</sub> = 1.6mA V <sub>LBI</sub> > 1.18V, I <sub>LBO</sub> = -1μA	V+ -1		0.4	V	
CTL Input Threshold	V <sub>CTL</sub>			0.7		V	
PR Output	V <sub>PR</sub>	PR High, I <sub>PR</sub> = -1μA PR Low, I <sub>PR</sub> = 1mA		V <sub>OUT</sub> - 0.2 0.3		V	

### Operating Principle

The MAX654-659 are step-up converters; energy from a battery is first stored in a coil and then discharged to the load. Essentially, the circuit consists of a battery in series with a coil (L2) and switch (LX2), along with a rectifier (D1) and filter capacitor (C1) as shown in Figure 1. When the switch is closed, current builds up in the coil, creating a magnetic field. Next, the switch opens, the magnetic field collapses, and the voltage across the inductor reverses polarity. This voltage adds to that of the battery and supplies current to the load via the rectifier.

The switch is controlled by a constant frequency oscillator whose output is gated on and off by a comparator that monitors the output voltage. When V<sub>OUT</sub> rises above the comparator threshold, the MOSFET at LX2 is held off.

The key to operating CMOS circuitry from a 1V supply depends on a technique called bootstrapping. A specially designed oscillator starts itself up on a very low

voltage and builds up (or bootstraps) a higher voltage that in turn is used as the supply for further operation. The bootstrapped supply yields higher efficiency because it can drive the gate of the internal FET transistors to lower on resistances.

When power is first applied, the circuit is very inefficient for the first cycle until a higher voltage is generated on the flyback half of the cycle. This higher voltage is rectified and filtered and powers the entire IC (and thus the oscillator) for the next cycle. Since each cycle generates a higher voltage for the next cycle, the voltage builds up very rapidly. An internal regulator limits the voltage to about 12V. The load for this supply is only the CMOS chip itself, so the requirements for the external inductor, L1, are not demanding. The +12V supply is brought out to the V+ pin and is connected to a tantalum capacitor for filtering.

The bootstrapped 12V drives an internal N-channel power FET that furnishes the switching power for the load.

# Low Voltage Step-Up DC-DC Converters

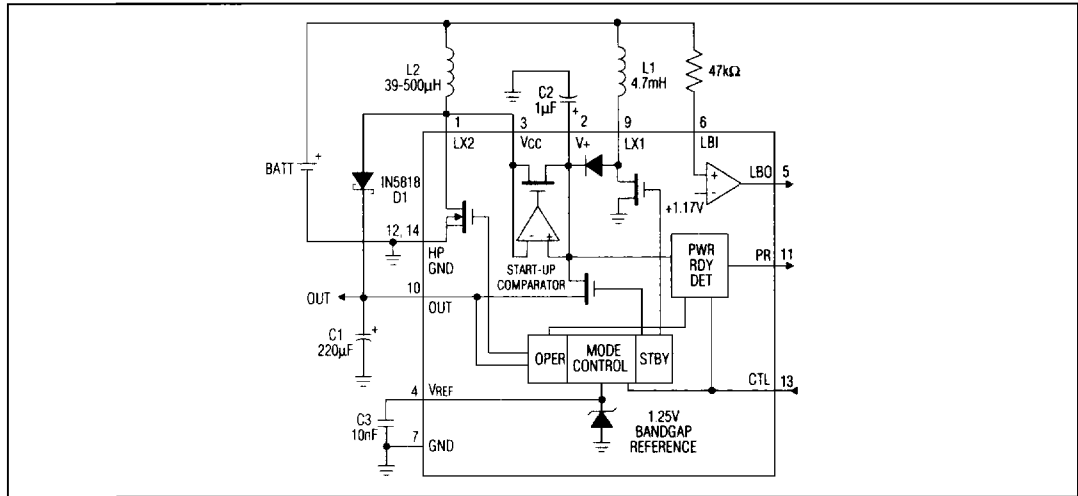


Figure 1. MAX654/655/657/659 Block Diagram

Since the gate of this FET is driven from a 12V supply, it has a very low on resistance and can efficiently switch high currents through a second inductor, L2. It is the power stored in this second inductor that is delivered to the 5V load via an external Schottky diode. The rectified 5V output is connected back to the OUT pin to provide

feedback. The MAX654-659 thus have two separate switching circuits and use two separate inductors.

### Circuit Details

A typical application circuit is shown in Figure 3. The higher value inductor, L1, is typically 4.7mH, and may

### Pin Description

MAX656 MAX658 PIN #	MAX654 MAX655 MAX657 MAX659 PIN #	NAME	FUNCTION
-	1	LX2	Output (drain) of high-power N-channel power MOS switch.
1	3	VCC	Start-up Bias Input; MAX654/655/657 connect to LX2. MAX656/658: connect to drain of external MOSFET.
2	2	V+	Output of low power-up converter; 10V to 15V in high-power mode; 4.5V to 5.6V in MAX654/655/656/658 standby mode; 2.6V to 3.6V in MAX657/59 standby mode.
3, 7	7	GND	Low-Power Ground.
4	4	VREF	1.25V bandgap reference output; should be decoupled with a capacitor to pin 3. This terminal is high impedance and cannot source or sink current.
5	5	LBO	Low Battery Monitor Output. Sinks 1.6mA when LBI is less than 1.17V, otherwise sources 1µA from V+.

MAX656 MAX658 PIN #	MAX654 MAX655 MAX657 MAX659 PIN #	NAME	FUNCTION
6	6	LBI	Low Battery Monitor Input 1.17V threshold.
8, 14	8	N.C.	No Connection.
9	9	LX1	Output (drain) of low-power N-channel power driver.
10	10	OUT	+5V (+3V on MAX657/659). Feedback (input) pin for high-power operation; output pin in standby mode.
11	11	PR	Power Ready Output; high when high-power converter is ready to supply power. High output level = V <sub>OUT</sub> .
-	12, 14	HP GND	High-Power Ground.
13	13	CTL	Control Mode Switch Input; open circuit or high for standby mode, ground for high-power mode.
12	-	D	Driver output to external FET. Output voltage swings from GND to V+.

# Low Voltage Step-Up DC-DC Converters

MAX654-659

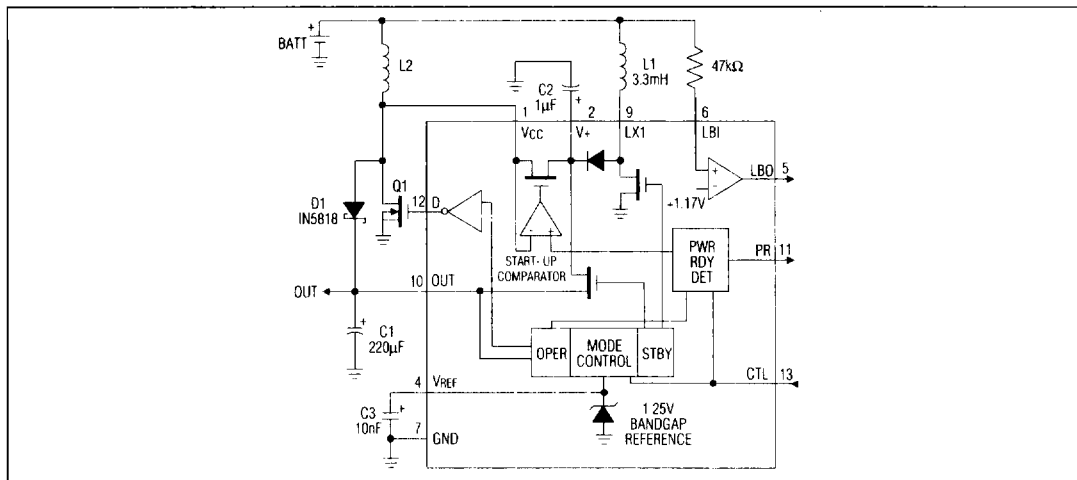


Figure 2. MAX656/658 Block Diagram

have fairly high losses. It is used for the low-power section of the circuit and is rectified by an internal diode and routed to V+, where it is filtered by an external capacitor, C1. The second inductor, L2, ranges from 12µH to 500µH, depending on input voltage and load current. It must have low series resistance and have sufficient core material to handle the load power without saturating. With the MAX654/5/7/8, the inductor, L2, is connected to LX2, which is simply the drain of the high-power FET. Current flowing through L2 is rectified by an external Schottky diode, D1, and filtered by an external capacitor, C2. This is the main +5V output (+3V on the

MAX657/659). It is connected to the OUT pin which is the feedback input in high-power mode. Figure 4 shows a similar circuit with the MAX656 using an external FET for higher power output.

## Low-Power Standby Mode

A control pin (CTL) puts the device into standby mode to conserve power. When this pin is held low, the IC operates normally. But if it is driven high or left open, the chip goes into standby. Several things happen in standby mode: the PR pin is driven low, the high-power FET is gated off, the 12V (V+) switching supply is reduced to

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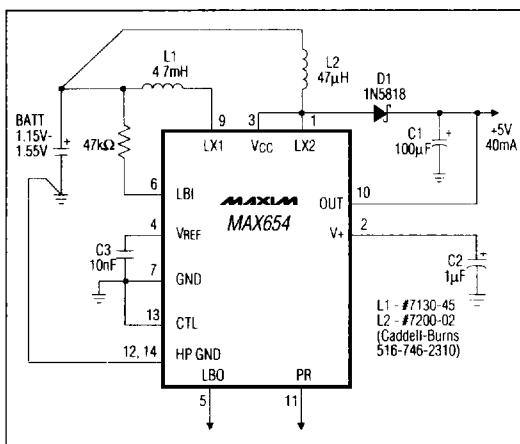


Figure 3. MAX654 Typical Application

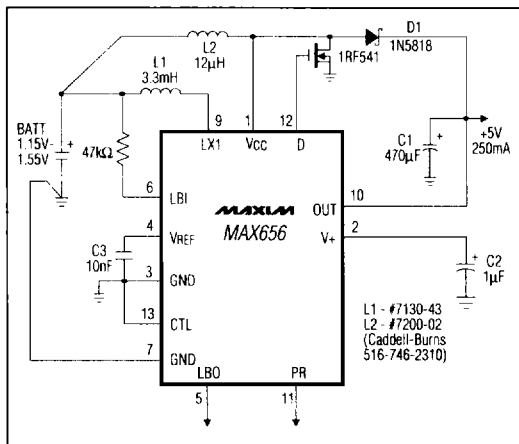


Figure 4. MAX656 Typical Application

## Low Voltage Step-Up DC-DC Converters

+5V (+3V on the MAX657/659) and is connected to the OUT pin. By lowering the internal 12V supply to 5V, the leakage currents of the CMOS circuits (and the losses associated with its voltage reference and oscillator) are reduced to a minimum. The internal low-power 5V supply can furnish up to 500 $\mu$ A and is connected to the normal 5V OUT pin to supply current to standby circuitry.

### Power Ready Output Pin

During initial start-up (and when placed in standby mode), the MAX654-659 internal voltages are too low to drive the power FET efficiently. A separate comparator determines when this voltage has reached a high enough value to drive the power FET. The output of this comparator gates the FET drive signal. This scheme extends battery life in standby mode and prevents the power FET from stalling when switching to high-power mode. The comparator output appears at the PR pin and can be used to control external circuitry, such as the gate of a MOSFET connecting the load to the power supply, further reducing battery drain.

### Start-Up and Mode Considerations

The MAX654-659 may be started up in either low-power (standby) or high-power mode. When starting in the high-power mode, both the low-power switch and the high-power switch start immediately. Whether or not the load is connected, the output voltage will rise to 5V in the first few cycles. Note that in the high-power mode, the OUT pin is used as a feedback input.

If a high-power load (greater than about 500 $\mu$ A) is connected to the OUT pin and the device is placed in the low-power mode via the CTL pin, the low-power oscillator will have to furnish all of the 5V power via the OUT pin, and the low-power oscillator will stall. Therefore, it is important to disconnect any load currents (greater than 500 $\mu$ A) whenever the low-power or standby mode is selected. The PR pin may be used to disconnect the load via an external transistor.

### Input Filtering

It is important to limit the rate of rise of the input voltage if the circuit is first turned on with a mechanical switch or by the installation of battery(ies). A simple R-C network made up of the battery's internal resistance and a 10 $\mu$ F tantalum capacitor placed at the battery side of L2 input is sufficient for this purpose. This capacitor also helps to absorb the (relatively) high peak currents that are drawn from the battery in the high-power mode.

### Output Filtering

An output reservoir capacitor must be placed on the OUT pin to provide filtering for the 5V output. Capacitor values should be 100 $\mu$ F or greater, with low effective series resistance to minimize output ripple. The V+ pin (12V) should be filtered with a 1 $\mu$ F capacitor, tied between the V+ pin and ground.

### Low Battery Function

A completely independent low battery monitor is built into the MAX654-659. Its input, LBI, is the + input of a CMOS comparator whose input is connected to an internal 1.17V reference. This input can be connected directly to the battery in single-cell circuits. The trip voltage of the Low Battery Detector may be adjusted using an external voltage divider as shown in Figure 5. The output, LBO, can sink 1.6mA or source several microamperes from V+. Place a 47k $\Omega$  resistor in series with the LBI pin.

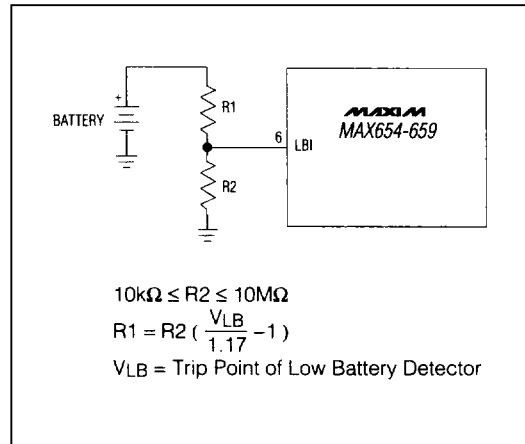


Figure 5. Setting Low Battery Detector Trip Point

## Inductor Selection

### Low-Power Coil, L1

For the low-power inductor (L1) a 4.7mH coil with a DC resistance of less than 40 $\Omega$  is adequate for most applications. In general, higher inductance values allow lower start-up voltages, while lower resistances yield lower quiescent current in standby mode. If the inductance is made too high, the low-power (V+) output voltage and current are reduced. This in turn reduces the efficiency of the power section, so the +5V output (in standby mode) supplies less current. Lower values of inductance raise the minimum start-up voltage.

### High-Power Coil, L2

The high-power coil, L2, stores most of the energy that flows into the load. Accordingly, it should have a powdered iron or ferrite core and have low series resistance to minimize losses. It also must have an adequate current rating to prevent saturation.

## Low Voltage Step-Up DC-DC Converters

A coil must be selected that keeps the peak current at LX2 below the maximum rating of the switch. This maximum is 1.5A for the MAX654/55/57/59 and depends on the current rating of the external FET and inductor when using the MAX656/58. The optimum inductance can be found using Figures 6-11 (refer to the Output Current vs. Input Voltage Section), or inductance values may be approximated from Table 1, or finally, the inductance may be calculated as follows:

The first step is to calculate the minimum permissible inductance that keeps the peak current below the current rating of the individual components. This is done using the highest expected input voltage ( $V_{IN(MAX)}$ ), the longest on time per cycle for the LX2 switch ( $t_{ON(MAX)}$ ), and the lowest total series resistance,  $R_{MIN}$ , where  $R_{MIN}$  is the sum of the minimum coil and FET resistances. These are the conditions under which the highest coil current flows.

For the MAX654, from the Electrical Characteristics table:

$$\begin{aligned} I_{pk} \text{ of LX2} &= 1.5A \\ R_{DS(ON)(MIN)} &= 0.4\Omega \\ f_0(MIN) &= 15,500Hz \\ \text{duty cycle maximum, \%ON(MAX)} &= 0.8 \\ t_{ON(MAX)} &= 46\mu s \end{aligned}$$

Assume that the minimum coil resistance,  $R_{COIL(MIN)}$  is:

$$R_{COIL(MIN)} = 0.1\Omega$$

The minimum total resistance,  $R(MIN)$  is:

$$R(MIN) = R_{DS(ON)(MIN)} + R_{COIL(MIN)} = 0.4 + 0.1 = 0.5\Omega$$

Then:

$$I_{pk} = 1.5A = \frac{V_{IN(MIN)}}{R(MIN)} \times [1 - e^{-R(MIN) t_{ON(MAX)} / L(MIN)}]$$

or:

$$L(MIN) = \frac{-R(MIN) t_{ON(MAX)}}{\ln \left[ 1 - \frac{I_{pk} R(MIN)}{V_{IN(MAX)}} \right]}$$

The above two equations "blow up" if  $R(MIN) = 0$ , but work fine for  $R(MIN) \geq 0.001\Omega$ . For a maximum input voltage of 1.56V (single alkaline cell) and a minimum coil resistance of  $0.1\Omega$ , the minimum permissible inductance for the MAX654/57 is 35.1 $\mu$ H.

Having determined the minimum inductance that keeps the peak current below the individual component ratings, we next calculate a new peak current ( $I'_{pk}$ ) using the highest resistance ( $R(MAX)$ ) and the lowest input voltage ( $V_{IN(MIN)}$ ). Using these parameters, we will calculate the minimum available output (DC) current.

From the Electrical Characteristics table:

$$\begin{aligned} R_{DS(ON)(MAX)} &= 0.67\Omega \\ f_0(MAX) &= 24,000Hz \\ \text{duty cycle minimum, \%ON(MIN)} &= 0.66 \\ t_{ON(MIN)} &= 30\mu s \end{aligned}$$

The inductance tolerance of L2 has some impact on these calculations. In the following equations, a new  $L(MIN)$  based on the manufacturer's tolerance specification is used. This example assumes  $\pm 10\%$  tolerance, so 90% of the nominal inductance is used.

Assume that the maximum coil resistance,  $R_{COIL(MAX)}$  is:

$$R_{COIL(MAX)} = 0.15\Omega$$

The maximum total charging resistance,  $R(MAX)$  is:

$$R(MAX) = R_{DS(ON)(MAX)} + R_{COIL(MAX)} = 0.82\Omega$$

At the end of the ON period:

$$I'_{pk} = \frac{V_{IN(MIN)}}{R(MAX)} \times [1 - e^{-R(MAX) t_{ON(MIN)} / L(MIN)}]$$

The energy stored in the in the coil is:

$$E_{COIL} = \frac{L(MIN) \times I'_{pk}{}^2}{2}$$

And the power put into the coil is:

$$\begin{aligned} P_{COIL} &= f_0(MAX) \times E_{COIL} \\ &= \frac{L(MIN) \times I'_{pk}{}^2 \times f_0(MAX)}{2} \end{aligned}$$

The minimum available DC output current,  $I_{OUT}$ , is:

$$\begin{aligned} I_{OUT} &= \frac{P_{LOAD}}{V_{LOAD}} = \frac{P_{COIL} - P_{LOSS}}{V_{OUT(MAX)} + V_{DIODE} - V_{IN(MIN)}} \\ &= \frac{P_{COIL} - I'_{pk}{}^2 \times R_{COIL(MAX)} / 3 \times (1 - \%ON(MIN))}{V_{OUT(MAX)} + V_{DIODE} - V_{IN(MIN)}} \end{aligned}$$

Using a  $47 \pm 10\%$   $\mu$ H coil with a resistance of  $0.15\Omega$  and an input voltage of 1.1V, the minimum available 5V output current at the highest output voltage (5.5V) would be 36.3mA. This assumes a 0.3V forward drop in the 1N5818 diode.

When selecting a coil, care should be exercised to insure that the minimum inductance value, including all the manufacturing tolerances, is never lower than the calculated inductance. Otherwise, the peak current rating of LX2 may be exceeded. In addition, the current rating of the coil should be greater than the peak current used in the calculation (1.5A normally) to avoid saturating the core.

If the worst case output current is too small, either the minimum input voltage must be increased or the maximum input voltage should be decreased. It is always desirable to decrease the ratio between maximum and

# Low Voltage Step-Up DC-DC Converters

**Table 1. Operation with Common Batteries**

MAXIM PART #	BATTERY TYPE	BATTERY VOLTAGE		OUTPUT		COIL SPECIFICATIONS (L2)		
		MIN	MAX			$\mu\text{H}^*$	OHMS	PART #
MAX654	1 NiCad	1.15V	1.35V	5V	43mA	39	0.05	6860-08
MAX654	1 Alkaline	1.2V	1.55V	5V	43mA	47	0.05	6860-09
MAX654*	1 Alkaline	1.2V	1.55V	5V	10mA	120	0.14	6860-14
MAX655	2 NiCads	2.3V	2.7V	5V	64mA	68	0.07	6860-11
MAX655	2 Alkalines	2.4V	3.1V	5V	62mA	82	0.07	6860-12
MAX655	1 Lithium	2.6V	3.6V	5V	64mA	100	0.10	6860-13
MAX656**	1 NiCad	1.15V	1.35V	5V	250mA	12	0.025	6860-02
MAX656**	1 Alkaline	1.2V	1.55V	5V	275mA	12	0.01	7200-02
MAX657	1 Alkaline	1.2V	1.55V	3V	60mA	39	0.05	6860-08

\* Coils are from Caddell-Burns Co. NY (516) 746-2310. Inductance ( $\mu\text{H}$ ) is the MINIMUM allowed for the listed battery voltage range (Battery Voltage: MIN, MAX). Lower values are not recommended, except when using the MAX656/658 converters since they use an external MOSFET. If less current than listed in the Output column is needed, a higher inductance coil will reduce losses. The optimum inductance varies inversely with required output current if all other conditions are unchanged. For example, refer to line 3 and the 10mA output. 120 $\mu\text{H}$  supplies this current more efficiently than the 39 $\mu\text{H}$  coil of line 2. L2 may also be calculated using the equations in the Inductor Selection Section.

\*\* These MAX656 circuits (see Figure 4) use an IRF541 as an external current switch. Peak switch current is typically 3.5A.

minimum input voltages. The coil resistance also has a significant effect on the output current. So, selecting a coil with the lower resistance will increase the output current and increase the overall efficiency.

If no satisfactory value of inductance can be found for the desired output current, the MAX656/58 may be used with an external FET whose current rating exceeds 1.5A. The calculations are similar for the MAX654, except the external FET's R<sub>DS(on)</sub> and the current rating of the FET or coil (whichever is lower) should be substituted in the above equations.

If the worst case output current is significantly higher than the required load current, a higher inductance value should be used. This will tend to reduce the peak current and ripple voltage, and tend to raise the overall efficiency. Be sure to adjust the coil resistance and recalculate all values when using another coil.

When the maximum battery voltage exceeds 1.65V, the MAX655/58/59 should be used. Calculations are identical to the MAX654 calculations, except different values must be used for the duty cycle and  $t_{\text{ON}}$ .

In general, if a choice of batteries is available, higher input voltages are preferred for two reasons. First, as the input voltage approaches 1V, the load on the battery increases while the losses increase. The losses become so dominant that efficiency suffers, and little output current can be maintained. Second, certain losses, such as the coil resistance and the FET on resistance, are less significant with higher input voltages. This means higher efficiency and a greater range of input voltages are tolerable. This in turn means that more of the chemical energy can be converted into electricity.

The inductance values for commonly encountered battery-operated power supplies are tabulated in Table 1.

## Capacitor Selection

The high-current, fast rise time pulses associated with switching power supplies demand good grounding and bypassing techniques. The MAX654-658 have 3 ground pins to improve grounding. In addition, the internal voltage reference is brought out for connection to an external 10nF capacitor, minimizing noise and modulation of the reference.

In order to minimize transients, the two output voltages, V+ and +5V, should be filtered with tantalum capacitors or other types of capacitors with low effective series resistance. If aluminum electrolytic capacitors are used, they should be paralleled with 0.1 $\mu\text{F}$  disc ceramic capacitors.

## Rectifier Selection

The MAX654-659 use one external rectifier. To achieve specified performance at low voltages, a Schottky type, such as the 1N5818, is recommended because it combines low forward voltage drop with fast switching speed. This maximizes power conversion efficiency and output current when the DC-DC converter is in high-power mode. One drawback of Schottky rectifiers is relatively high reverse leakage current (at 5V reverse, 1N5818 leakage is typically 60 $\mu\text{A}$  at 25°C and 450 $\mu\text{A}$  at 75°C), which is quite large with respect to the circuit's quiescent current in standby mode (typical standby current MAX654/56/57: 80 $\mu\text{A}$ , MAX655/58/59: 40 $\mu\text{A}$ ). If standby mode is not used or used only for short periods, reverse leakage is not a significant additional loss compared to the normal load current, and need not be considered.



# Low Voltage Step-Up DC-DC Converters

If quiescent operating current is a primary concern, or if the MAX654-659 spends most of its time in standby mode, a silicon rectifier such as the 1N4933 or Unitrode UES1001 may be preferred. Silicon rectifiers have less reverse leakage current than do Schottky rectifiers (1N4933 leakage current is typically 1 $\mu$ A at 25°C and 50 $\mu$ A at 100°C). In circuits where the standby mode is the predominant mode of operation, battery life may be extended by trading conversion efficiency for lower standby quiescent current.

## Output Current vs. Input Voltage

Figures 6 through 11 show output current versus input voltage using typical inductor values for each part in the MAX654-659 Family. Where curves end in the middle of the graphs, the peak current limit of the internal LX2 switch has been reached. A higher input voltage than indicated by that line (for the given inductor) may damage the device. Figures 8 and 10 assume that an IRF541 MOSFET is used (0.085 $\Omega$  maximum on resistance).

Dashed lines indicate regions where the LX2 current limit hasn't been exceeded, but the current rating of the selected coil (Caddell-Burns 6860 series) has. The actual voltages where lines end or become dashed are indicated by arrows on the graphs. The output currents indicated by dashed lines can be achieved only with inductors of higher current rating than the indicated coil (such as Caddell-Burns 7200 series or a toroid, for example). The coils used in Figures 6, 7, 9, and 11 are as follows:

- |                       |                |
|-----------------------|----------------|
| 33 $\mu$ H - 6860-07  | Caddell-Burns  |
| 47 $\mu$ H - 6860-09  | (516) 746-2310 |
| 100 $\mu$ H - 6860-13 |                |
| 150 $\mu$ H - 6860-15 |                |
| 220 $\mu$ H - 6860-17 |                |

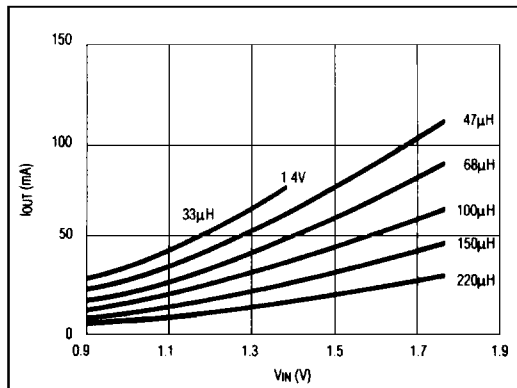


Figure 6. MAX654,  $I_{OUT}$  vs.  $V_{IN}$  ( $V_{OUT} = 5V$ )

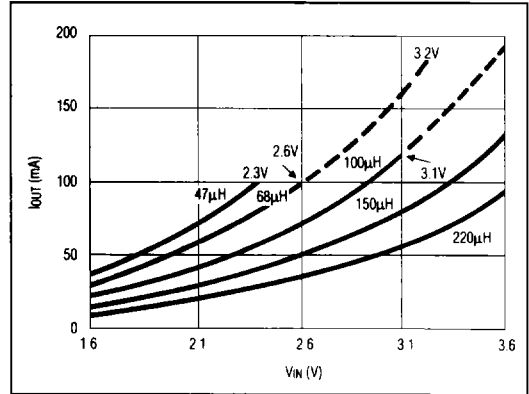


Figure 7. MAX655,  $I_{OUT}$  vs.  $V_{IN}$  ( $V_{OUT} = 5V$ )

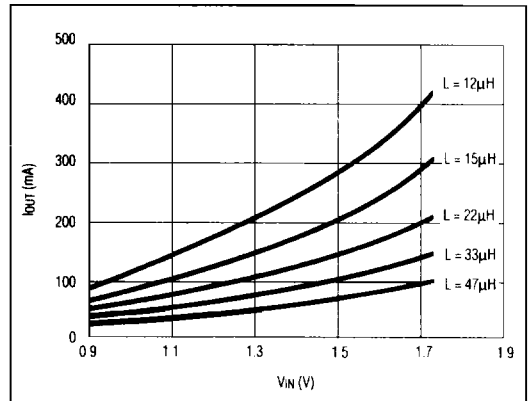


Figure 8. MAX656,  $I_{OUT}$  vs.  $V_{IN}$  ( $V_{OUT} = 5V$ )

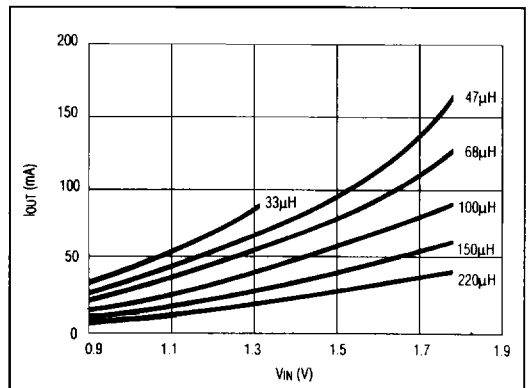


Figure 9. MAX657,  $I_{OUT}$  vs.  $V_{IN}$  ( $V_{OUT} = 3V$ )

# Low Voltage Step-Up DC-DC Converters

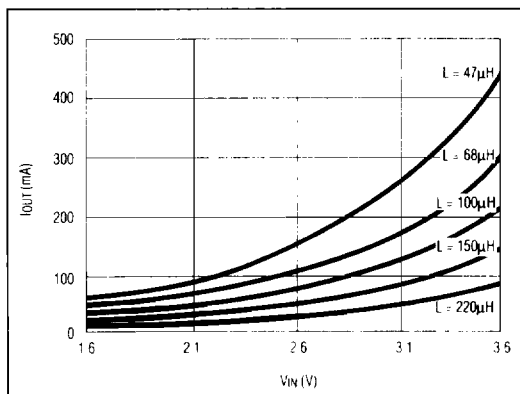


Figure 10. MAX658,  $I_{out}$  vs  $V_{IN}$  ( $V_{out} = 5V$ )

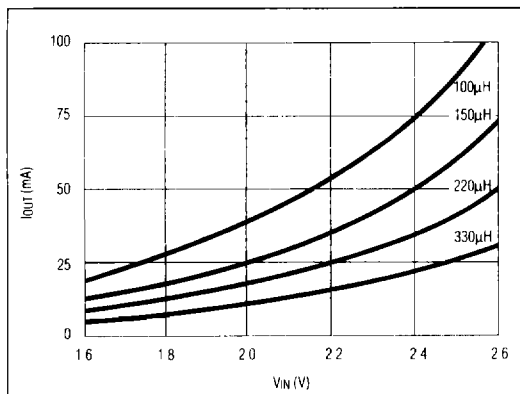


Figure 11. MAX659,  $I_{out}$  vs  $V_{IN}$  ( $V_{out} = 3V$ )

The coils used in Figures 8 and 10 are the Caddell-Burns 7200 series inductors.

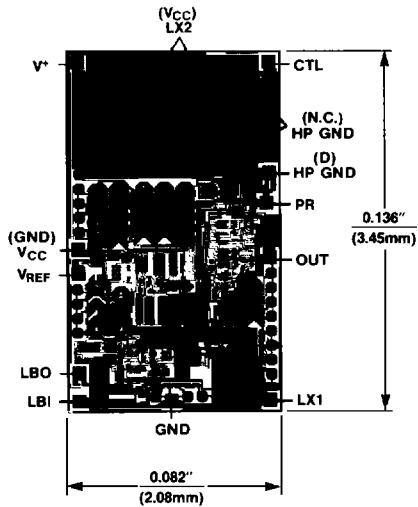
The graphs in Figures 6-11 were calculated using worst case data, so individual circuits may supply more current than indicated. If the coils' current ratings are not exceeded, smaller, lower-cost coils than those indicated may be used in low-current applications. Use the equations in the text to calculate worst case peak coil/switch current to be sure that a particular coil's current rating is sufficient.

## Ordering Information (continued)

PART	TEMP. RANGE	PIN-PACKAGE
MAX656CPD	0°C to +70°C	14 Plastic DIP
MAX656CSD	0°C to +70°C	14 Narrow SO
MAX656C/D	0°C to +70°C	Dice
MAX656EPD	-40°C to +85°C	14 Plastic DIP
MAX656ESD	-40°C to +85°C	14 Narrow SO
MAX656MJD	-55°C to +125°C	14 CERDIP
MAX657CPD	0°C to +70°C	14 Plastic DIP
MAX657CSD	0°C to +70°C	14 Narrow SO
MAX657C/D	0°C to +70°C	Dice
MAX657EPD	-40°C to +85°C	14 Plastic DIP
MAX657ESD	-40°C to +85°C	14 Narrow SO
MAX657MJD	-55°C to +125°C	14 CERDIP
MAX658CPD	0°C to +70°C	14 Plastic DIP
MAX658CSD	0°C to +70°C	14 Narrow SO
MAX658C/D	0°C to +70°C	Dice
MAX658EPD	-40°C to +85°C	14 Plastic DIP
MAX658ESD	-40°C to +85°C	14 Narrow SO
MAX658MJD	-55°C to +125°C	14 CERDIP
MAX659CPD	0°C to +70°C	14 Plastic DIP
MAX659CSD	0°C to +70°C	14 Narrow SO
MAX659C/D	0°C to +70°C	Dice
MAX659EPD	-40°C to +85°C	14 Plastic DIP
MAX659ESD	-40°C to +85°C	14 Narrow SO
MAX659MJD	-55°C to +125°C	14 CERDIP

# Low Voltage Step-Up DC-DC Converters

## Chip Topography



**Note:** Labels in ( ) are for MAX656/MAX658 only

MAX654-659